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A comparison of uniform and 3-D tyre contact pressure representations using a finite element method

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Abstract

In pavement engineering a crude uniform contact pressure over a circular contact area is used to generate key strains for an analytical design method. The use of a more advanced tyre contact pressure measurement device has led to a situation where there is more information that is available to generate a more accurate uniform representation of contact pressure. This measurement device also offers the ability to measure non-uniform 3-D tyre contact pressure. That is to say the vertical, transverse and longitudinal components of pressure generated by a tyre in contact with a pavement. A comparison of the key strains generated by this improved uniform contact pressure representation and the measured 3-D contact pressure is of great interest. Of course a tyre does not display the same contact pressure for different combinations of axle loading and inflation pressure. The combination of these two factors greatly affects the nature of the contact pressure observed. A finite element mesh of a 3-layer thin pavement structure was created in CAPA-3D. This was used to model the uniform and 3-D contact pressure representations of a wide based tyre. This was done for 3 inflation pressures and 3 tyre loads. The inflation pressures were for a recommended inflation pressure and then plus and minus 200 kPa. The tyre loading was for a maximum European axle loading and then greater and lower than this value. This gave a good spread of conditions that are relevant to the tyre operating conditions. The key strains at different locations in the pavement relevant to the major distresses of a pavement were assessed. The main distress mechanisms being top down cracking, asphalt cracking/rutting, traditional bottom up cracking and subgrade rutting. These gave a good spread of possible distresses that tyre contact pressure can contribute to. The results showed that there was a large effect on surface strains caused by 3-D contact pressure in comparison to uniform contact pressure for all combinations of inflation pressure and tyre loading. The difference between the two contact pressure representations diminished with depth in the pavement. Therefore, it was clear that 3-D contact pressure has an effect on the distress of a pavement surface.

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This means to accurately understand the deterioration of a pavement surface, 3-D contact pressure must be considered. In the case of the other distresses the uniform contact pressure generated greater strains and would give a conservative pavement design. Both methods generated greatly different key strains depending on the combination of inflation pressure and tyre loading. If a complex highly accurate analysis is required, then a fully 3-D representation in combination with finite element analysis is the best option. However, if a more routine analysis is required then the improved uniform contact pressure representation could be used with a simple modelling tool (e.g. BISAR) to get good results for a traditional analytical design.

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1. Introduction

The increase in traffic is leading to increased deterioration of roads. There is also the problem of how the pavement design industry represents tyre pavement contact pressure. These two problems are leading to roads that underperform and the design life of which is greatly unpredictable. A good representation of 3-D tyre contact pressure is a great leap forward from what is currently used in design. There needs to be further investigation to understand how detailed and how accurately 3-D contact pressure is modelled to create more predictable roads for the increasing traffic volumes.

True tyre contact pressure is composed of vertical, transverse and longitudinal contact pressures. The largest component of stress is the vertical contact pressure, the next largest is the transverse contact pressure and the smallest is the longitudinal contact pressure (Pottinger, 1992; De Beer et al., 1997; Myers et al., 1999; Blab, 1999; Fernando et al., 2006; Wang & Roque, 2010). The transverse and longitudinal contact pressures are similar in magnitude with the vertical component being much larger. The 3-D non-uniform contact pressure is in stark contrast to the representation of contact pressure as a uniform circular contact pressure in current design methods (Powell et al., 1984; Theyse et al., 1996). It is shown that these non-uniform contact pressures are of importance to the behaviour of pavements especially on the surface and near surface (Siddharthan and Sebaaly, 1998; Perret, 2002; Novak et al., 2003a; Park et al., 2005; Luo and Prozzi, 2006). The conditions that are created in the near surface are greatly different from these for uniform conditions and could lead to rutting and cracking in these regions (Perret, 2002; Luo and Prozzi, 2006; Al-Qadi and Wang, 2012). It has been shown that there are significant differences to surface cracking potential caused by non-uniform contact pressure (Collop and Cebon, 1995; Casey et al., 2012; Casey et al., 2014).

The magnitude of these 3-D contact pressures has been shown to be highly influenced by the tyre type, tyre loading and inflation pressure (Marshak, et al., 1985; Pottinger, 1992; De Beer et al., 1997; Blab, 1999; De Beer et al., 1999; Novak et al., 2003b; Fernando et al., 2006; Douglas et al., 2008; Wang & Roque, 2010). An individual tyre can have a large range of vertical, transverse and longitudinal contact pressure depending on the inflation pressure and tyre loading (Prozzi and Luo, 2005; Fernando et al., 2006). This means that to characterise pavement behaviour to truck loading a combination of tyre types, inflation pressures and tyre loading is needed to assess the behaviour of a specific truck axle (Blab, 1999; De Beer, 2006). An area of interest is also the quantification of pavement behaviour under the different components of 3-D contact pressure for different tyres, inflation pressures and tyre loading. The literature presented shows there has been some work in this area, but that it is sporadic and lacks a European perspective. This work compares dual tyres to new wide base tyres for the US market (Fernando et al., 2006; Al-Qadi and Wang, 2012). In Europe the wide base tyre has been adopted and the effect of this for using 3-D contact pressure needs to be examined. This is what this paper sets out to do.

2. Objectives

This paper uses a 3-D and a uniform representation of wide based tyre contact pressure for different combinations of axle load and inflation pressure. This is to understand the effects these contact pressures have on the pavement behaviour. The key objectives of the paper to assess the effects are:

- To compare the maximum shear strain readings generated on the pavement surface. This allows for the effects of the contact pressure has on the pavement surface to be investigated
- To compare the maximum shear strain readings generated in the asphalt between 30-80 mm from the surface. This allows for the effects contact pressure has on the pavement in the near surface to be investigated.
- To compare the maximum tensile strain readings generated at the bottom of the pavement for the longitudinal and transverse direction. This allows for the effects contact pressure has on pavement bottom up cracking.
- To compare the maximum compressive strain generated on the top of the subgrade. This allows for the effects contact pressure has on subgrade rutting.

These measures act as a method comparing the two contact pressure representations for key areas for the performance of a pavement for the major forms of pavement distress.

3. Method

The model in this paper utilises a static loading, a linear-elastic material model, a simple pavement structure and an intricate 3-D contact pressure loading technique using a finite element method. There is 1 tyre used for the trailer axle. The tyre is loaded for 3 inflation pressures and 3 axle loadings. This gives a good scope of tyres used on the European road network for trailer axles of trucks. It also gives a spread of inflation and tyre loading conditions that addresses the variation that can exist in practice.

A tyre is designed to be used for certain axles and as such will only ever be subjected to a specific range of loads and inflation pressures. This axle is a trailer axle that consists of a wide base radial tyre 425/65R22.5. The tyre represents a typical European articulated truck consisting of super single trailer tyres using a wide base 425/65R22.5. A 425 tyre can have an inflation pressure of 720 kPa for its respective tyre load. The trailer axle is legally permitted to have an axle load of up to 10 tonnes depending on the vehicle layout and the European country. These values give a basis to conduct a comparison of the relative aggression of this axle to a specific mode of distress.

The loads used are from a software package called Tireview from the Texas Transportation Institute (Fernando et al., 2006). This is a library of contact pressures from the VRSPTA (Vehicle-Road Surface Pressure Transducer Array) stress in motion sensor for different tyres, axle loads and inflation pressures using an interpolation to predict contact pressure between these measured combinations for specific tyres. There is a common low tyre load of 26 kN, which is the lowest load available in the Tireview software. The trailer axle has a medium tyre load of 49 kN (equivalent axle load of 10 tonnes) and a high tyre load of 53kN (equivalent axle load of 11 tonnes). This sets up the tyre load levels that are to be investigated. This matrix of loading is shown in Table 1.

To represent the non-uniform contact pressure as an equivalent uniform circular contact patch a procedure was used that utilises the measured contact area estimation from Tireview and the applied tyre loading (Fernando et al., 2006). There is another procedure which represents the contact pressure based on the tyre load and the inflation pressure but this would have given greatly unsuitable results and was not chosen for this research on these grounds. This other method overestimates the contact area for low inflation pressure and underestimates the area for high inflation pressure (Fernando et al., 2006). The method presented here gives a contact pressure based on the tyre loading and the area of the uniform loading is based on the measured contact pressure and from that the radius of the contact patch is given. The equations used are presented here (Fernando et al., 2006):

$$P_e = \frac{P}{A_m} \quad (1)$$

$$r_e = \sqrt{\frac{A_m}{\pi}} \quad (2)$$

Where: P = applied tyre load,
 A_m = measured tyre contact area,
 P_e = equivalent uniform circular contact pressure, and
 r_e = radius of equivalent circular contact area.

The results from these equations for each of the tyre types, axle loads and inflation pressures are given in Table 1.

The pavement is modelled as a three-layer system with an asphalt layer, a sub-base layer and a subgrade layer. The asphalt layer is 150 mm in thickness, the sub-base is 300 mm and the subgrade layer is assumed to behave as a semi-infinite layer but for the purposes of the model is 2m deep (Fig. 1). This is a simple pavement structure that is of reasonable composition for a regional road and could be classed as a thin pavement structure. These types of pavements are of importance for the UK and other developed nations, where the majority of the network of local and regional roads is of a comparable structure. This choice of pavement gives good scope for the results of the analysis performed to be of use to the pavement industry.

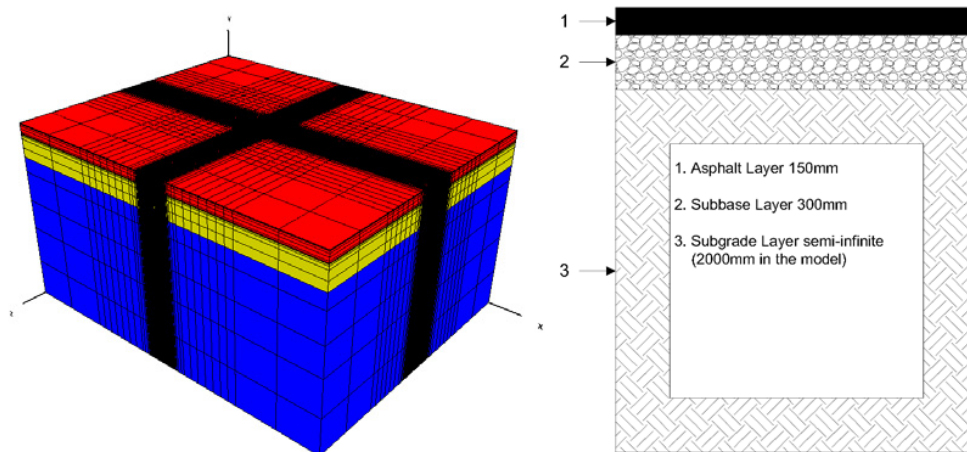


Fig. 1. 3-D image of the simple pavement structure and pavement structure.

The material properties for the pavement are isotropic linear elastic and represent values that would be typical for such layers and for the type of pavement. The asphalt modulus is 7500 MPa with a Poisson's ratio of 0.35. These values represent good quality asphalt at lower temperatures. The elastic component of asphalt's material behaviour is dominant for a short loading time and lower temperatures. The sub-base layer is a good quality crushed aggregate granular layer with adequate confinement pressure to give an elastic modulus value of 690 MPa and Poisson's ratio of 0.35. This represents a well laid, well drained and adequately compacted layer. The subgrade layer is modelled as a semi-infinite layer with a modulus of 100 MPa and a Poisson's ratio of 0.35.

The finite element analysis utilises a 4 m x 4 m and 2.45 m deep finite element mesh consisting of 20-noded quadratic elements using full integration (Scarpas et al., 2004). The mesh is fixed in all directions at the base and restrained in the lateral direction at the sides. The contact area is set to match the discretisation of the raw contact pressure data, which is 15 mm in the longitudinal direction and 17 mm in the transverse direction (Fig. 2). The area with this density of elements extends 850 mm in the transverse and 900 mm in the longitudinal direction symmetrically around the centre of the mesh on the pavement surface.

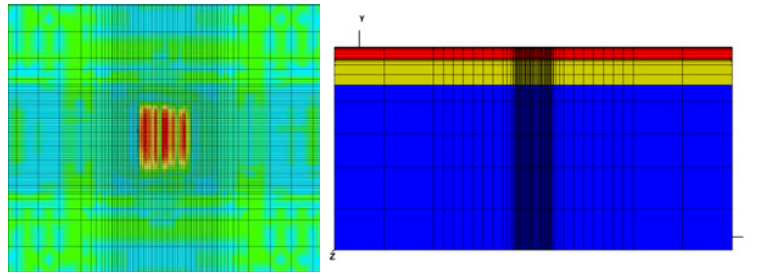


Fig. 2. Refinement of the top of the mesh and cross-section of the pavement.

As can be seen in Fig. 2 there are a large number of elements used in this analysis and it uses considerable memory resources for it to be run. The total number of elements in the mesh is 132,600.

Table 1. Loading options for the input contact pressures for the 3-D contact pressure and the uniform contact pressure representation.

Tyre, tyre load and inflation pressure		Uniform Loading Pressure kPa	Radius of Uniform Contact Patch mm
Trailer Tyre Half Axle Load kN	Inflation Pressure kPa		
	26	520	
	49	720	
	53	950	
		632	115
		729	107
		884	97
		823	138
		907	131
		1026	123
		845	141
		926	135
		1038	128

The 3-D contact pressure loading method works by matching the mesh dimensions to the dimensions of the discretisation in the loading area of the mesh (fig.3). The contact pressure was divided into 17 mm (transverse) x 15 mm (longitudinal) areas of uniform contact pressure representing the raw contact pressure readings from Tireview.

This discretisation activity reduces the density of contact pressure data to a reasonable density for use in finite element analysis, but it must also maintain the nature of the raw data. This was checked for each of the contact pressures used to assure that this reduced data remains reasonably close to the raw data.

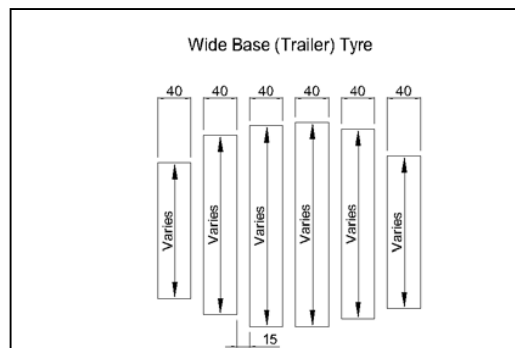


Fig. 3. An outline of the tyre ribs locations and dimensions (mm) of the 425 wide based tyre.

The stress and strain outputs for the model for a simple circular contact pressure were compared against BISAR, and they compared excellently against each other. This showed that the model behaves well and the mesh density and boundary conditions are stable.

The model was run for the combinations of loading factors presented in Table 1. These scenarios represent different factors of tyre, load, inflation pressure and components of contact pressure. There were over 45,000 strain output values recorded for each run of the model. The areas of interest were on the surface of the asphalt layer, to a depth between 30-80 mm in the asphalt layer, the bottom of the asphalt layer and the top of the subgrade layer. The procedures and the model layout presented here represent a good basis for the goals of this part of the research.

4. Results

The previous section shows that there are key areas of interest to gauge the performance of a pavement. These areas can be used as markers to compare other factors such as a uniform circular representation of tyre contact pressure. This is a useful comparison as it answers two key questions. Does this representation of a tyre's contact pressure over/under estimate the damaging potential? What areas of the pavement need full 3-D contact pressure representation? There were 9 loading combinations for each contact pressure used in this comparison.

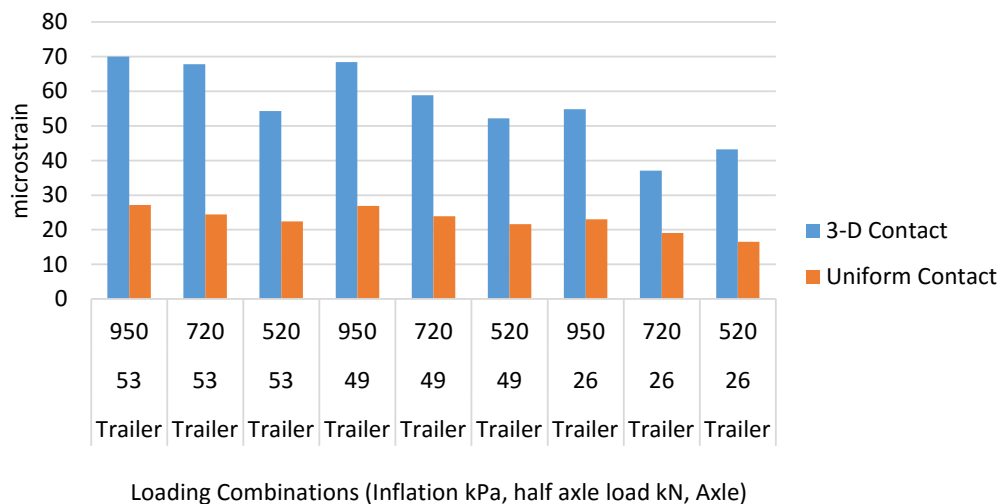


Fig. 4. Comparison of the maximum surface shear strain for 3-D and uniform contact pressure for the trailer axle.

The difference between the uniform contact pressure and 3-D contact pressure for surface vertical shear strain was pronounced across all the loading combinations of the trailer axle. The difference in the average strain between the two contact pressures was 34 microstrain giving an 84% percentage difference between them (Fig. 4). The percentage difference was calculated as the average of the two values being compared divided into the difference between the values and then multiplied by 100 to give a percentage value. This means that the uniform contact pressure would greatly underestimate the potential for top-down cracking caused by surface shear strain. The magnitude of the range of values is such that the underestimation could be vast in terms of pavement life. This highlights that to understand the behaviour of a pavement on the surface then proper 3-D representations of the true contact pressure are required to guard against underestimation of the potential for pavement deterioration.

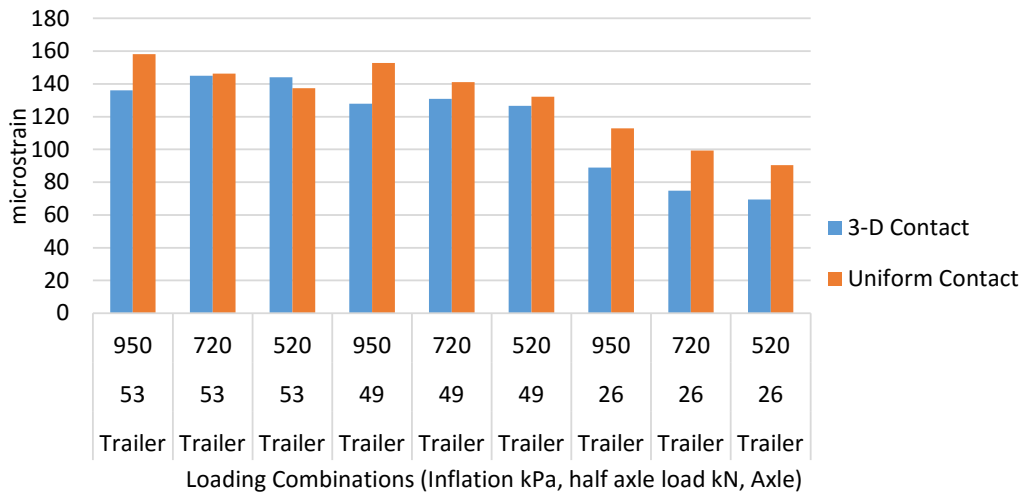


Fig. 5. Comparison of the maximum asphalt shear strain for 3-D and uniform contact pressure for the trailer axle.

The Trailer axle values for the maximum asphalt shear strain see a reversal of positions for the two contact pressure representations. The uniform contact pressure now has the highest values overall with an average of 130 microstrain and the 3-D representation has 116 microstrain (Fig. 5). This gave a percentage difference between the two of 15%. The values are close compared to the surface shear and are not as worrying.

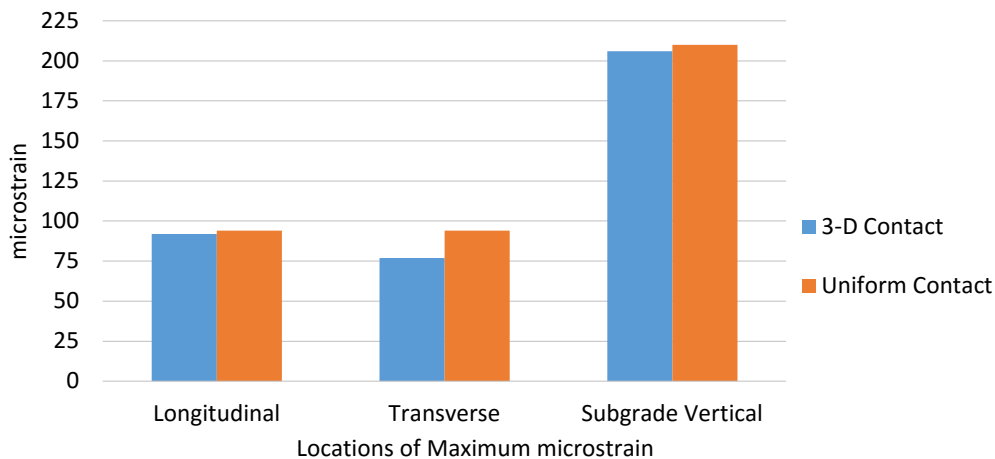


Fig. 6. Comparison of average maximum longitudinal and transverse tensile strain at the bottom of the asphalt and average maximum vertical strain on the top of the subgrade for 3-D and uniform contact pressure.

The longitudinal tensile strain at the bottom of the asphalt showed that the two representations of contact pressure agree rather well to each other when considering the simplification required (Fig. 6). The transverse tensile strain at the bottom of the asphalt gave rise to greater differences between the two contact pressure representations than for the longitudinal component (Fig. 6). The difference between values for the trailer axle was 17 microstrain. This gave percentage difference of 20%. There was considerable difference between the three axles suggesting that the uniform contact pressure representation does not model the trailer axle adequately.

In the case of the vertical compression on the subgrade the two contact pressure representations were very close (Fig. 6). The uniform representation was slightly higher for each of the axles providing some extra reassurance as to the validity of a design made using these values. The uniform contact pressure representation would be allowable as a representation of the contact pressure based on this evidence.

5. Discussion

The surface shear strain was greatly different for the two contact pressure representations (Fig. 4). The uniform contact underestimated the contact pressure for all of the axle loadings and inflation pressures. This demonstrates that a uniform contact pressure is not suitable for estimating surface shear strain. The uniform contact pressure cannot recreate the complex nature of 3-D contact pressure and as such at this location will greatly underestimate the strain and by extension the potential for it to cause damage. The shear strain in the asphalt showed much better agreement between the two contact pressures (Fig. 5). The uniform pressure overestimates the values but not by a great deal. It created conservative strain measurements for this particular area and strain.

The two strain measurements agreed rather well for the longitudinal tensile strain at the bottom of the asphalt layer (Fig. 6). The uniform contact pressure again overestimates the strain but not to a great degree. The difference between the transverse tensile strains at the bottom of the asphalt layer was much greater (Fig. 6). The uniform contact pressure once again overestimated the strain in comparison with the 3-D contact pressure. These overestimations would lead to a conservative pavement design and capital being spent to provide a deeper asphalt pavement where it is perhaps not needed. The final comparison was for the compressive strain on the top of the subgrade (Fig. 6). This gave a slight overestimation by the uniform contact pressure for the three axles. This variation is slight but is still statistically significant.

The question is whether there is an appetite in the pavement industry to use more advanced analysis techniques, input loads and transfer equations to assess a pavement more completely. If risk can be limited and commercial advantage can be demonstrated more advanced design techniques could be possible.

6. Conclusions

A number of conclusions can be drawn from the results of the analysis detailed in this paper. It is clear that there are significant differences in the behaviour of the pavement especially in the surface, the near surface region and transverse strain at the bottom of the pavement.

- A uniform circular representation of contact pressure greatly underestimates the values of shear strain on the pavement surface.
- A uniform representation of contact pressure overestimates the values of asphalt shear strain in the pavement and the transverse tensile strain at the bottom of the pavement.
- A uniform circular representation of contact pressure is a fair representation of longitudinal tensile strain at the bottom of the pavement and compressive strain on the subgrade.

The points listed above shows the representation of contact pressure has a serious influence on how strains are judged for different forms of pavement distress. It means that for surface cracking the uniform contact pressure would underestimate the potential and rate of cracking in comparison to the 3-D contact pressure. The uniform contact pressure would overestimate the potential of asphalt rutting and or cracking in comparison to the 3-D contact pressure. They both agree well for longitudinal tensile strain at the bottom of the pavement. This shows that it predicts the longitudinal bottom up cracking potential well. This is also true for the subgrade rutting. The transverse strain at the bottom of the pavement is much less for the 3-D contact pressure in comparison to the uniform contact pressure. This shows that the 3-D contact pressure exerts less strain transversely compared to the uniform contact pressure and the longitudinal. All this data highlights the importance of 3-D contact pressure in understanding surface and near surface pavement behaviour. The use of this more complex representation of contact pressure could lead to more predictable pavement designs.

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